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TECHNICAL REPORT BRL-TR-2842

A PROPULSION SYSTEM COMPARISON STUDY FOR THE 120-mm ANTI-ARMOR CANNON

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AUGUST 1987

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We explore the effect of advanced propulsion technologies on the performance potential of a 120-mm high performance cannon. The current 120-mm gun using conventional granular propellant operates at a peak pressure of 505 MPa and accelerates a 7.1 kg saboted projectile with a kinetic energy penetrator to a velocity of 1650 m/s. We predict that performance increases on the order of 25% are possible in theory for the best of the advanced propulsion concepts. In practice a 10 to 15% increase is a more realistic upper limit. The use of a 30% longer gun tube operating at a 15% higher peak breech pressure results in an almost 10% increase in muzzle velocity. Relatively small increases in muzzle velocity such as these can result in significant improvements in overall gun system effectiveness.

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I. INTRODUCTION

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It is the purpose of this study ~~to~~ examines the potential of advanced gun propulsion technologies for improving the performance of a 120-mm cannon. ~~We~~ It examines briefly the improvements possible by optimizing conventional granular propellant technology, and ~~we~~ also examines the limiting performance potential of conventional gun propulsion as represented by the idealized constant pressure (CP) gun requiring perfect surface area control. It ~~We~~ re-examines the improvements possible with the solid propellant traveling charge (SPTC) effect. Finally, in the same context, ~~we analyze~~ the performance of a regenerative liquid propellant gun (RLPG) is analyzed, and ~~While~~ none of these advanced technologies are mature enough at this point in time for fielding, they do represent the performance potential for future gun systems.

For anti-armor gun systems, kinetic energy (KE) penetrators have become the ammunition of choice. Basic armor penetration mechanics reveals that KE penetrators, which impact targets at velocities near the 50% perforation probability (v_{50}) limit, benefit greatly by small increases in muzzle velocity. Five to ten percent increases in striking velocity are important enough to justify substantial developmental efforts to realize them in practice.

We begin this study by defining some pertinent interior ballistic parameters of the current baseline 120-mm gun system and its standard round. We then present the ground rules for the parametric comparison of the advanced propulsion options. We first show representative interior ballistic trajectories for all of the propulsion options at the performance level of current standard ammunition. This provides insight into some of the important physical aspects involved. We then review the performance increases possible by varying the loading density. Each of these comparisons also examines the combined effect of operating at a higher pressure with a longer gun tube. We finally discuss the results and assess their implications.

II. GROUND RULES AND PROCEDURES

The pertinent interior ballistic parameters for a standard 120-mm gun system are shown in Table 1. These parameters were used to calibrate the interior ballistic codes. The calibration factors include heat loss, burning rate adjustments, and bore friction profiles. These were then frozen for the rest of the parametric study as appropriate. Three different computer codes were used for this study each requiring a somewhat different calibration approach.

TABLE 1. 120-mm Gun and Projectile Characteristics

In-Bore Projectile Weight (kg)	7.1
Bore Diameter (mm)	120
Maximum Projectile Travel (m)	4.75
Chamber Volume (l)	9.75
Peak Breech Pressure (MPa)	505
Muzzle Velocity (m/s)	1650

PROPELLANT CHARACTERISTICS

Types	JA2	FNC	KC	BEN
Weights (kg)	7.40	0.66	0.11	0.03
Impetus (J/g)	1140.	547.	286.	635.
Flame Temperature (K)	3410.	1610.	1054.	2000.
Specific Heat Ratio	1.225	1.258	1.273	1.250
Covolume (cc/g)	0.996	1.009	0.357	1.084
Density (g/cc)	1.578	0.941	0.941	1.661
Web (cm)	0.178	0.32	0.32	0.20
Number of perforations	7	1	1	0
Burn Rate Coef. (cm/(sec-MPa)	0.150	0.100	0.004	9947.
Burn Rate Exponent	0.95	1.00	1.00	0.0

Notes on Propellants:

JA2 - Granular high energy propellant
FNC - Felted Nitrocellulose Combustible Cartridge Case
KC - Kraft Paper Liner for Cartridge Case
BEN - Benite Igniter

The parametric calculations performed for the four propulsion options described below were done for two pairs of peak pressure and gun tube lengths. One is the standard case shown above; the other is an enhanced 120-mm gun postulated to operate at a nominal peak pressure of 579 MPa with a projectile travel of 6.274 meters. This may represent a practical upper bound for the growth potential of the current 120-mm gun.

1. IMPROVED CONVENTIONAL GUN

For the parametric analyses of the conventional gun, the complexities of the combustible case and ignition components were neglected and a solution using conventional, hexagonal, 19-perforated granular grains with JA2 propellant is shown. A revised version of the Baer-Frankle code,[1] called IBHVG2,[2] was used. IBHVG2 is a thermodynamic or lumped parameter interior ballistic code in which mass and energy conservation are explicitly treated, while the hydrodynamics of the two-phase gas flow are approximated by the Lagrange assumption of constant gas density. This propulsion option constitutes the baseline against which all others are to be compared.

2. CONSTANT PRESSURE GUN

The constant pressure gun represents the thermodynamic limiting performance of conventional gun propulsion. A special option of the IBHVG2 code allows either surface area or burning rate to be computed so that a specified pressure is maintained. It is the goal of consolidated and deterred propellant efforts to approach constant pressure operation. The thermodynamic parameters of the propellant were those for JA2 propellant, currently used in 120-mm ammunition.

3. SOLID PROPELLANT TRAVELING CHARGE GUN

The details of the traveling charge effect, its advantages and disadvantages, have been previously described.[5] For this concept to work as desired, a propellant with very high burning rate characteristics is attached to the projectile as shown schematically in Figure 1. The rapidly burning propellant produces thrust which, combined with the base pressure, accelerates the projectile. Typically, effective burning rates on the order of 100 to 200 m/s are required. The developmental efforts to obtain such propellants have been described by Juhasz.[4]

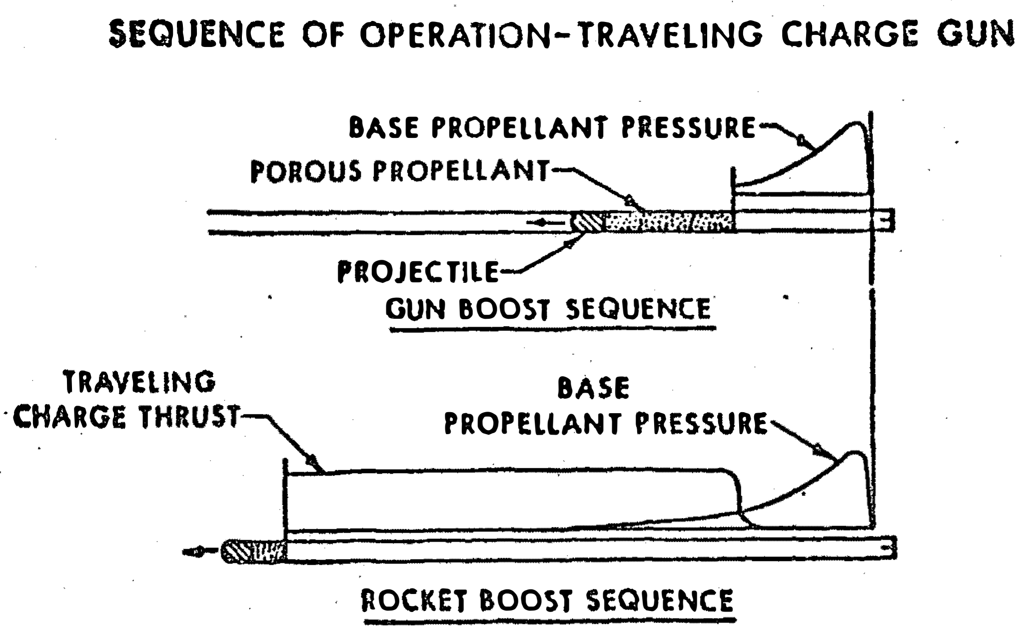

Figure 1. Traveling Charge Gun Concept

The parametric calculations for this propulsion concept were performed by a computer model called BRTC.[5] It is a one-dimensional, single phase flow model which assumes a thin reaction zone and planar surface regression. It assumes a linear elastic solid propellant response and includes a simple treatment of wall friction and heat loss. A special feature called the constant stress option was exercised. In this option the combined thrust plus projectile base pressure were kept constant. The propellant thermodynamic parameters of JA2 were used for all BRLTC calculations.

4. REGENERATIVE LIQUID PROPELLANT GUN

Details of the RLPG concept and experimental progress have been described by Morrison et al.[6] In the RLPG, a liquid propellant behind a piston is injected through orifices in the piston into a hot, high pressure combustion chamber. A schematic of the RLPG is shown in Figure 2. The high pressure LP spray is ignited in the hot chamber producing pressure which accelerates a projectile downbore. The piston area difference between the chamber and the reservoir maintains a positive pressure difference required for injecting the LP without external pressurization.

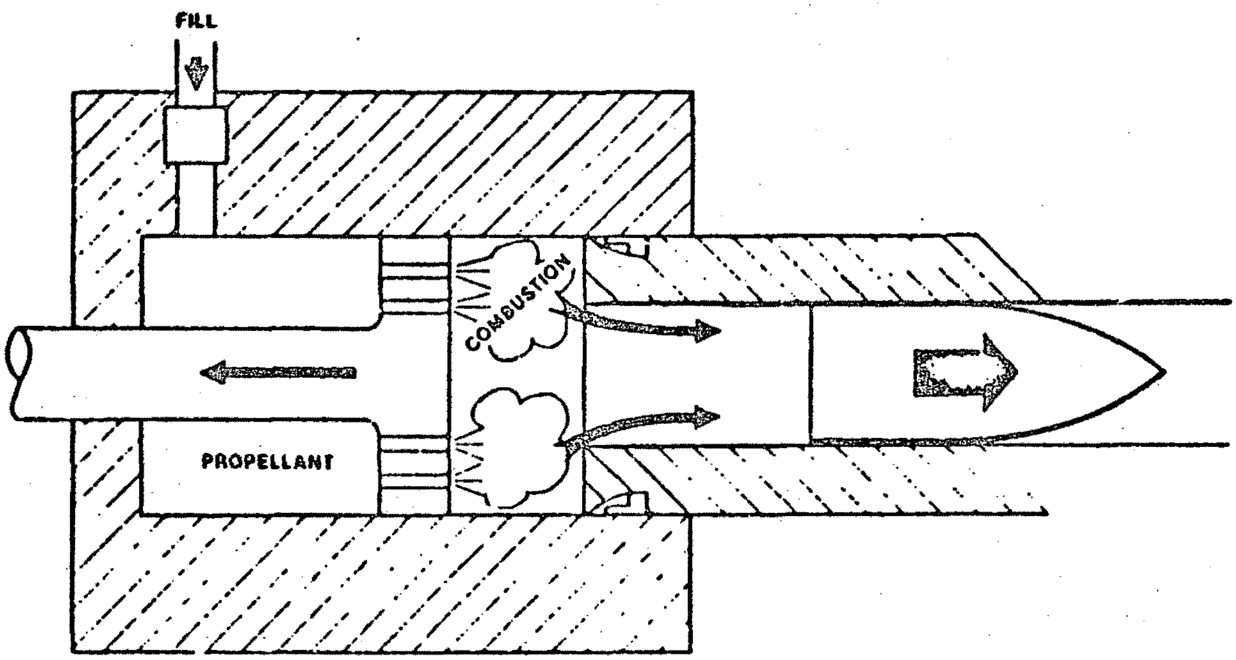

Figure 2. <u>RLP Gun Concept</u>

For the RLPG performance calculations a computer model, RLPTC, developed by Gough[7] was used. In this model the LP reservoir and the combustion chamber are treated as lumped parameter regions, while the barrel is modeled as a two-phase, one-dimensional flow region. Calculations were made for two propellants, a hypothetical "liquid JA2" and LGP 1845, a hydroxylammonium nitrate based liquid monopropellant of somewhat lower energy than JA2; see Table 2. The parameters adjusted in the calculations were total LP injection area, initial gas pressurization during the ignition phase, and shot start pressure. Piston mass was scaled from 105-mm experimental data. Parameters were adjusted to give nearly constant chamber pressure operation until propellant burnout. For this study, combustion of the injected liquid propellant was assumed to be instantaneous.

TABLE 2. Propulsion Systems Summary Baseline Cases

GUN AND PROJECTILE CHARACTERISTICS

Projectile Weight (kg)	7.1
Bore Diameter (mm)	120
Maximum Projectile Travel (m)	4.75
Chamber Volume (l)	9.75

Propulsion System	Conv.	CP	SPTC	RLPG
Propellant	JA2	JA2	JA2	LGP 1845
Weight (kg)	7.51	6.92	7.21	8.78
Impetus (J/g)	1140.	1140.	1140.	973.
Flame Temperature (K)	3410.	3410.	3410.	2695.
Specific Heat Ratio	1.225	1.225	1.225	1.215
Covolume (cc/g)	0.996	0.996	0.996	0.609
Density (g/cc)	1.578	1.578	1.578	1.462
PERFORMANCE				
Muzzle Velocity (m/s)	1650	1650	1650	1650
Max. Chamber Pressure (MPa)	505	505	505	505
Max. Gun Pressure (MPa)	505	505	505	705
Max. Proj. Base Pressure (MPa)	337	505	505	505

Figure 3 illustrates the interior ballistic trajectory for the 120-mm gun using conventional granular gun propellant. This is a typical plot for a high performance gun. The upper pressure-travel curve shows the breech pressure with a peak value of 505 MPa. The lower curve shows the projectile base pressure. It is the area under this second curve which represents the work done on the projectile, hence its kinetic energy. The pressure difference between the two curves is due to the finite speed of sound in this hot, high pressure medium. The magnitude of the pressure difference is determined by the choice of the Pidduck-Kent approximation in IBHVG2.

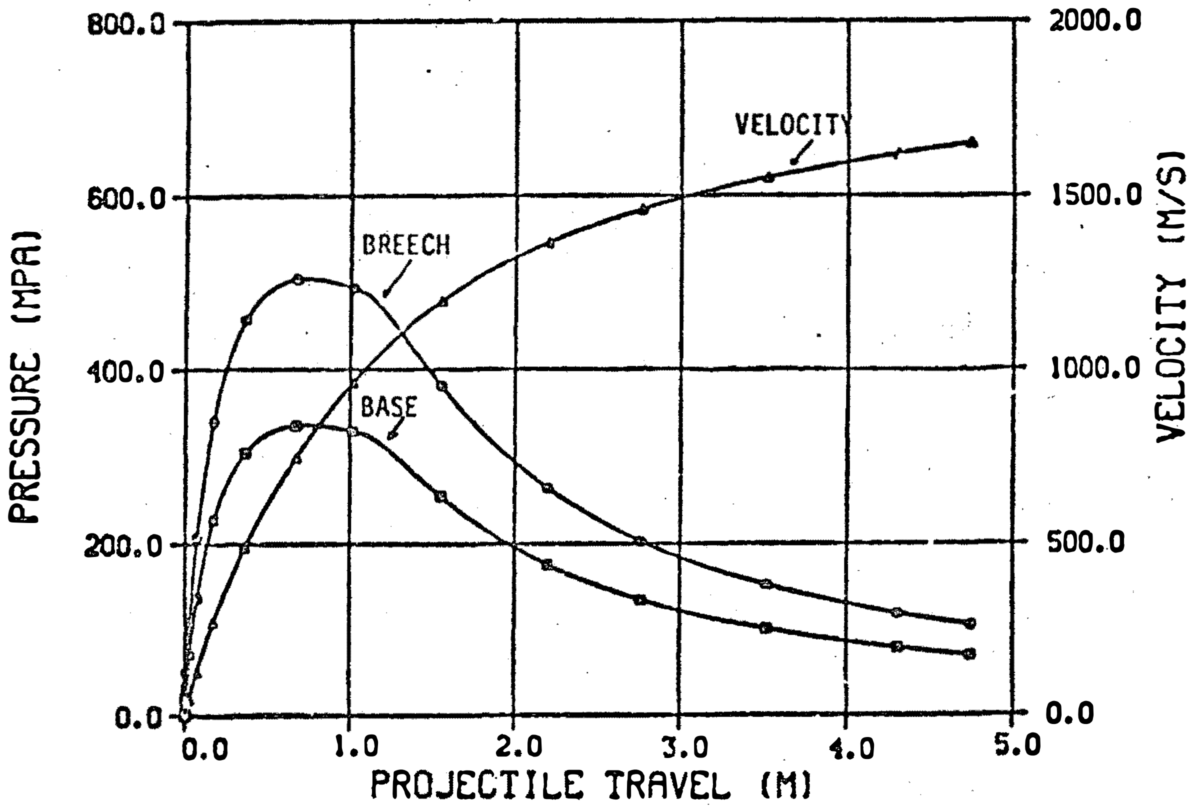

Figure 3. Interior Ballistic Trajectory for Conventional 120-mm Gun Propulsion Using 19-Perforated JA2 Propellant.

Figure 4 illustrates the ideal interior ballistic trajectory for the 120-mm gun assuming constant pressure operation. For a given set of interior ballistic parameters using conventional propellant and propulsion technology, one cannot obtain better results in terms of efficiency. The burning rate is calculated to give the necessary gas generation rate required to keep the breech pressure constant in the face of the ever expanding volume as the projectile moves downbore. At propellant burnout the problem is reduced to adiabatic expansion. The pressure gradient between the breech and the projectile base is, of course, very similar to the standard conventional propellant case.

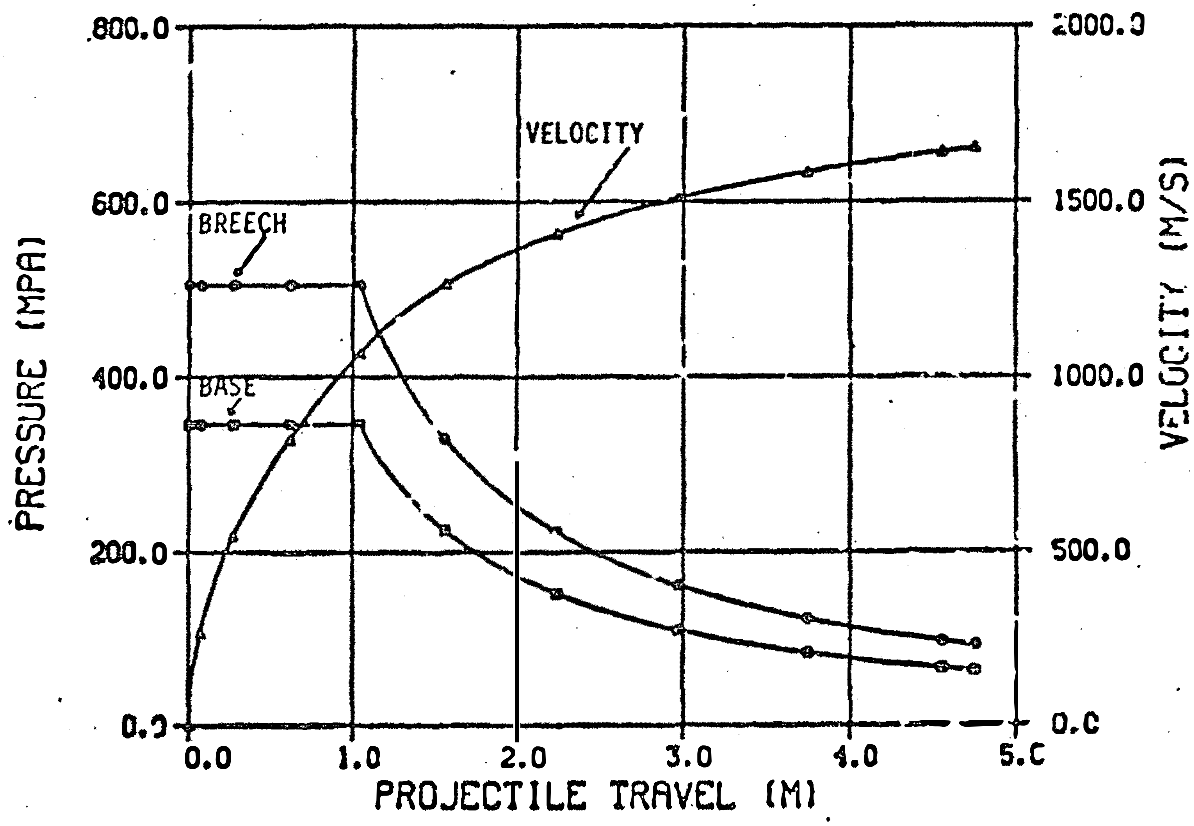

Figure 4. Interior Ballistic Trajectory for an Ideal 120-mm Constant Pressure Gun Using JA2 Propellant.

The interior ballistic trajectory of a 120-mm gun driven by the traveling charge effect is illustrated in Figure 5. As mentioned earlier, in this concept a cylinder of very high burning rate propellant (VHBR) attached to the projectile, provides the propulsion necessary to accelerate the projectile. In this plot we show the stress, breech, and projectile base pressures as a function of projectile travel. In this simulation the gun chamber is pressurized to its peak value before motion of the projectile is permitted. Thereafter, the burning rate is calculated to keep the total stress at the propellant surface constant until burnout. This stress pressure is the sum of the impulse, or thrust, due to the rapidly regressing propellant surface and the gas pressure near the same surface. While the stress pressure remains constant, the breech and projectile base pressures decrease with increasing projectile travel.

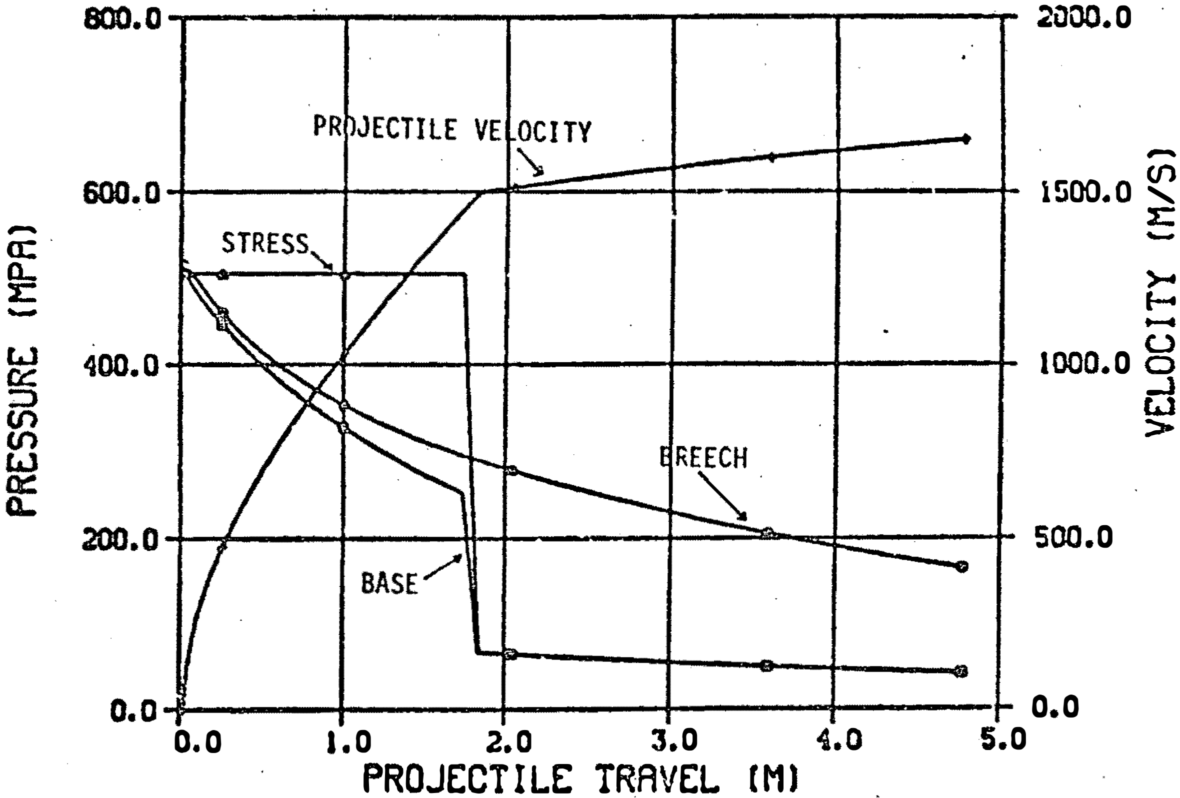

Figure 5. Interior Ballistic Trajectory for an Idealized 120-mm Traveling Charge Gun

Figure 6 illustrates the interior ballistic trajectory of a 120-mm gun using the regenerative liquid propellant gun (RLPG). Shown in this plot are: (1) the liquid propellant reservoir pressure; (2) the combustion chamber pressure; (3) the projectile base pressure; and (4) projectile velocity; all are shown as a function of projectile travel. The maximum chamber pressure is kept at the same peak value of 505 MPa as in the previous three cases. However, the peak LP reservoir pressure is 36% higher due to the piston area ratio between the chamber and the LP reservoir side of the piston. There is also a pressure gradient between the chamber and the base of the moving projectile. This pressure gradient is analogous to that exhibited in a conventional gun and is due to the momentum loss in moving the combustion gases down the bore. A major assumption in this simulation is that the liquid propellant burns instantaneously and completely upon injection from the lP reservoir into the combustion chamber.

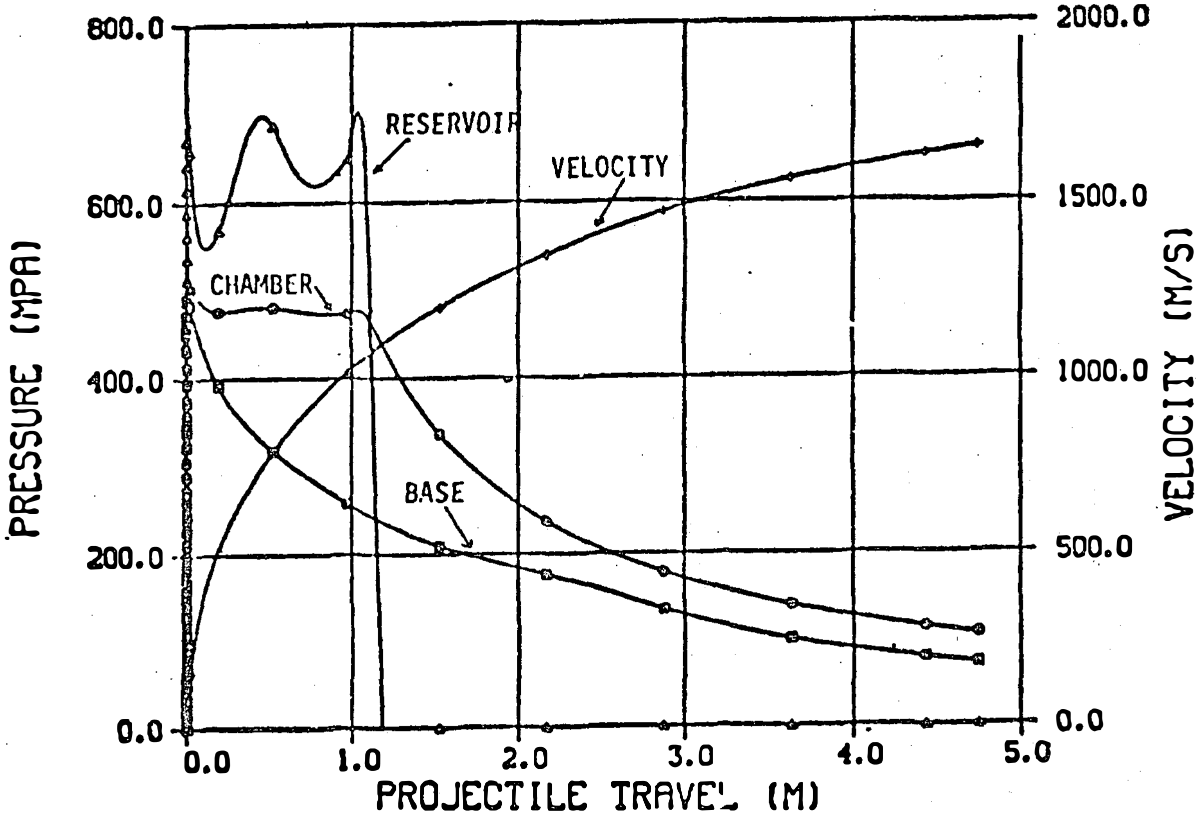

Figure 6. Interior Ballistic Trajectory for a 120-mm RLP Gun Using LGP 1845 Propellant.

The effect of loading density on the muzzle velocities for the four propulsion systems is illustrated in Figures 7 and 8. The constraints are fixed peak chamber pressure, projectile travel, JA2 propellant thermodynamics, projectile weight, and chamber volume. Figure 7 shows the results for the current 120-mm gun, and Figure 8 shows the results for the enhanced 120-mm gun with its longer barrel and higher operating pressure. The chamber volume is kept the same for both the current and enhanced systems. We also present a comparison of the RLPG performance potential for a current liquid propellant in Figure 9. The two curves are for the hypothetical "liquid JA2" propellant and LGP 1845.

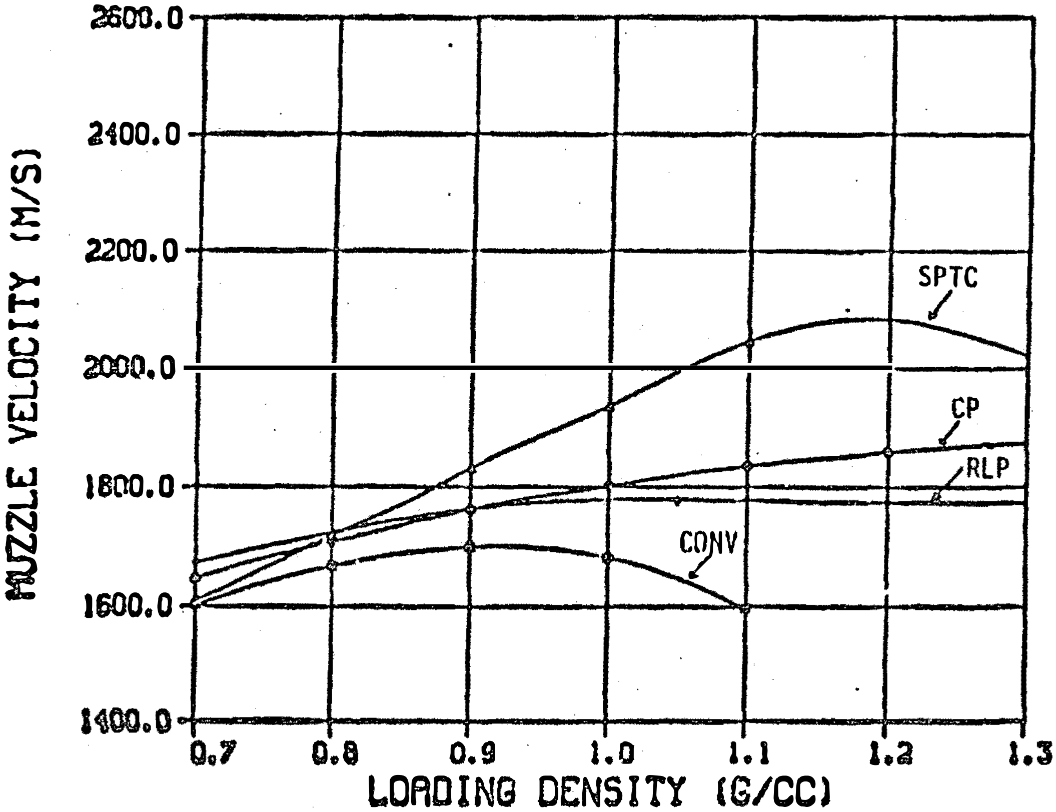

Figure 7. Effect of Increased Loading Density on Performance of Standard 120-mm Gun Using Four Propulsion Options.

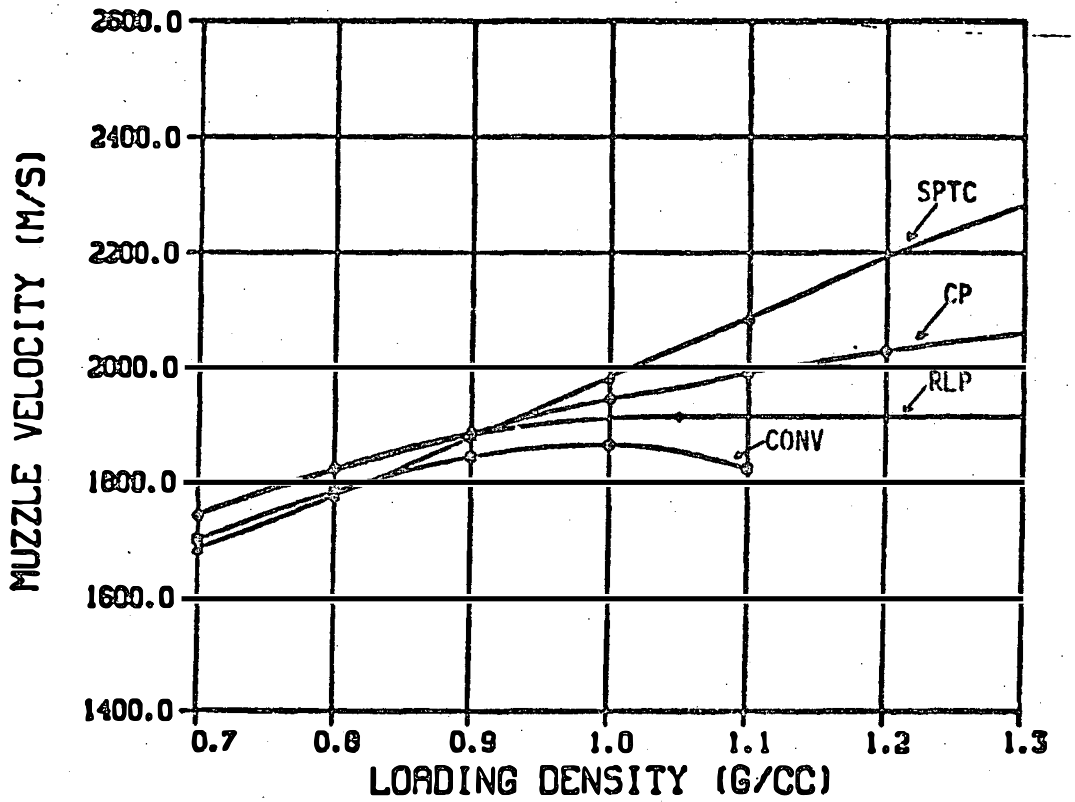

Figure 8. Effect of Increased Loading Density on Performance of Enhanced 120-mm Gun with Four Propulsion Options.

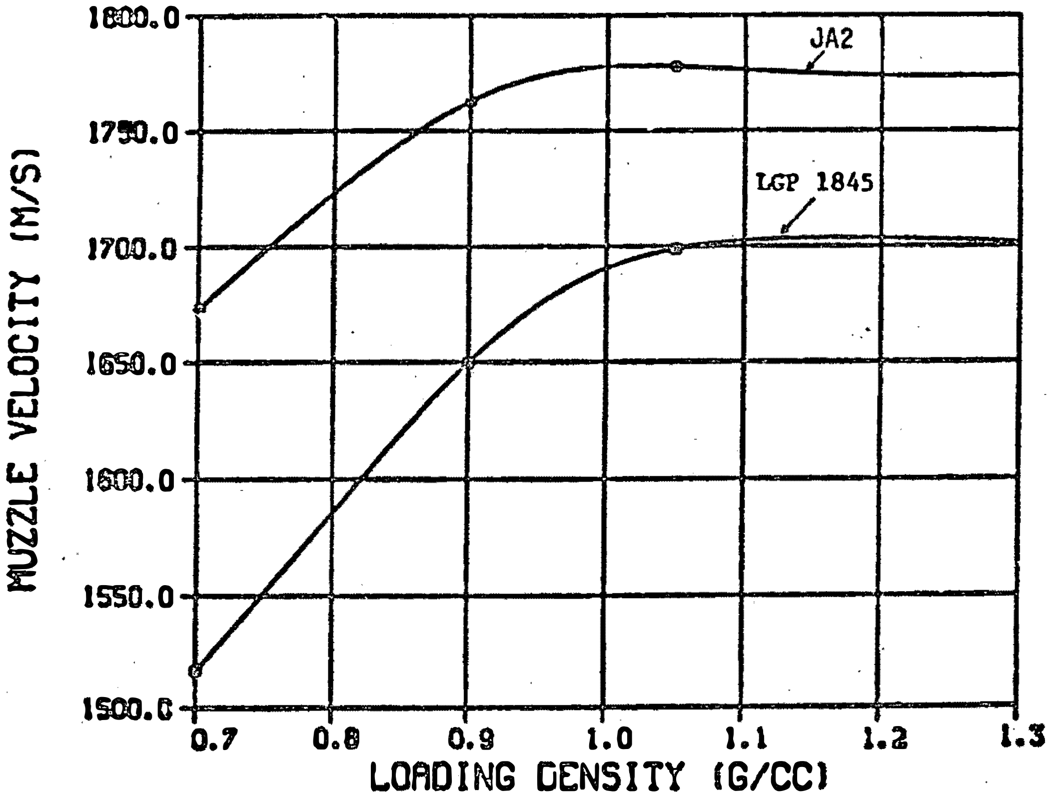

Figure 9. Effect of Propellant Thermochemistry on Performance of a 120-mm RLP Gun.

III. DISCUSSION

The results in this study indicate that for loading densities above about 0.9 g/cc, the best performance in the 120-mm gun is obtained by using the traveling charge gun, followed by the constant pressure gun, the RLPG and the conventional gun.

The constant breech pressure for the solid and regenerative gun simulations, and the constant stress solid traveling charge gun simulation represent an estimate of the upper limits on the performance one can achieve with these concepts. Given that different levels of physical approximations are made in the computer simulations used in this study, the magnitude of the resulting velocity differences at a given loading density may not be exact. However, the rank ordering of the results agrees with our intuitive understanding of the ballistic processes for the three advanced propulsion concepts. At high muzzle velocities, the available propellant is burned most effectively at the projectile base (SPTC), least effectively at the breech (RLPG), and with moderate effectiveness in the lumped parameter interior ballistic codes for the conventional and CP gun where it is assumed to be distributed between the breech and the base of the projectile.

It is also intuitively obvious that all propulsion options must collapse at low loading densities to the same muzzle velocity. When burnout of the propellant occurs before projectile motion begins, all expansion work is done on the projectile alone, and, therefore, the same muzzle velocity is obtained for all concepts.

The physical differences in the four propulsion techniques considered in this study are apparent in both Figures 7 and 8. However, these differences are more pronounced in the latter. At low loading densities, 0.7-0.9 g/cc, the traveling charge results in velocities comparable to the conventional charge. Above 0.9 g/cc, the benefit of the traveling charge at very high velocities becomes increasingly apparent. In contrast, the conventional result reaches a maximum and begins to decrease above 0.9 g/cc. The two constant pressure concepts give almost identical results below 0.9 g/cc, and both provide higher predicted velocities than either the conventional or SPTC cases. Above 0.9 g/cc, the RLPG curve flattens out rapidly while the constant pressure solid propellant curve continues to rise. In the constant pressure case, the imposition of the Pidduck-Kent pressure gradient implies that propellant combustion is distributed along the tube in such a way as to maintain the imposed gradient.

1. IMPROVED CONVENTIONAL GUN

The relatively flat pressure vs. travel curve shown in Figure 3 is the direct result of the progressive, 19-perforated grain geometry. In fact, the similarity to the CP gun curves of Figure 4 are striking. Except for the initial pressurization region, the curves are virtually the same. The ballistic efficiency of the optimized conventional gun is about 92% that of the constant pressure gun, or, in terms of velocity, the muzzle velocity of the optimized conventional gun is 96% that of the CP gun for the baseline case.

Figure 8 shows that the optimum loading density for the standard conventional gun is about .9 g/cc. Putting more propellant in the chamber actually results in a lower velocity because unburned propellant is being ejected. For the enhanced 120-mm gun shown in Figure 9, the optimum loading density increases to 1.0 g/cc, and the conventional gun curve stays closer to the CP gun limiting curve. As the peak operating pressure and the expansion ratio increase, the two curves will eventually collapse into one.

In a separate calculation, the muzzle velocity increase due to a longer gun tube alone is computed to be 5%, while the combined effect of a longer gun and higher pressure at the same loading density results in a 9% increase in velocity. This is a very desirable level of improvement.

In all of these calculations, we assume that the sabot mass is insensitive to changes in peak acceleration. In reality, increased peak base pressures require increased sabot mass which results in a reduced muzzle velocity. Fortunately, the trade-off is usually a net gain for modest changes.

2. CONSTANT PRESSURE GUN

As previously mentioned, the CP gun represents the performance limit for conventional gun propulsion for any given set of gun parameters. The CP muzzle velocity vs. loading density curves of Figures 7 and 8 show that large increases in velocity are possible at the high loading densities if one can find a way to burn the propellant in the required, highly progressive fashion. From a practical standpoint, the upper limit in loading density is about 1.25 g/cc for compacted or consolidated propellant. Indeed, experimental results suggest that for such propellants, the required surface area progressivity can be obtained through mechanical fracture and chemical deterrents.[8] Increases in loading density beyond 1.25 g/cc do not result in any significant velocity increases in any case.

While perfect constant pressure operation may be desirable, little performance will be sacrificed by slight deviations from the ideal. If one assumes that the overall efficiency for a high loading density "CP" charge is comparable to that of a conventional charge, a 6% velocity gain over an optimized granular round is possible. In fact, 10% velocity increases have been experimentally demonstrated for consolidated charge rounds in several different calibers.[8]

3. SOLID PROPELLANT TRAVELING CHARGE GUN

Figures 8 and 9 show quite clearly that the traveling charge propulsion concept offers the greatest performance increase, if the required propellants were available. Research efforts to date, while showing progress, have not yet yielded a safe and practical solution to this problem.

The traveling charge effect becomes more efficient than the other propulsion options at the high velocities because less energy is wasted in accelerating gases. In the SPTC, gases exit the propellant surface at high velocities with respect to the surface but at nearly zero velocity with respect to the barrel. For the other propulsion options considered, the gases at the projectile base must move at the same velocity as the projectile. At propellant burnout, the energy acquired in accelerating the mass of solid propellant attached to the projectile is, of course, redistributed among internal energy of the gases, kinetic energy of the bullet and, to a more limited extent, kinetic energy of the gases, heat loss, and other small irreversible energy losses.

Figure 5 shows the rather intriguing drop in base pressure at propellant burnout. A common misconception of the traveling charge propulsion concept is that muzzle pressures must be exceedingly high. This is not necessarily the case. At burnout the gases near the projectile are virtually at rest with respect to the barrel, hence after burnout they must suddenly accelerate. This causes the substantial pressure drop. Of course, the expansion work done on the projectile also suffers. It therefore pays to delay burnout to within a few calibers of the muzzle by reducing the peak operating stress.

It is also clear that the traveling charge concept is of little value at moderate performance levels. Only when muzzle velocities on the order of 2000 m/s are required, does it make sense to consider this propulsion concept.

4. REGENERATIVE LIQUID PROPELLANT GUN

The loading density results for the RLPG show trends very similar to the CP gun. This is not surprising since the injection area for the RLPG is adjusted to maintain virtually constant chamber pressure as shown in Figure 6. Oscillations in the reservoir pressure are due to the response of the spring-mass system, formed by the reservoir and piston, to the imposed start-up conditions.[9] In practice, low frequency spring-mass oscillations, similar to those in Figure 6 but much lower in amplitude, are observed in RLPG test firings.[10] Much higher frequency oscillations related to the liquid jet breakup and combustion processes are also observed in RLPG firings in most calibers.[10] It appears difficult to eliminate these oscillations completely. Due to the very high frequencies involved, breechblow hazards have not been associated with these oscillations as in solid propellant and bulk loaded liquid propellant guns.

The divergence of the RLPG curve from the CP curve in Figures 8 and 9 results from an interesting physical consideration. In the RLPG, gas generation takes place entirely in the chamber, and the pressure gradient in the barrel is defined by the acceleration of the combustion gases behind the projectile. Since a finite amount of time is required for communication between the combustion chamber and the projectile base, fluctuations in chamber pressure are not immediately sensed at the projectile base. In the case of the RLPG, it was observed that upon burnout a rarefaction wave moves from the breech toward the muzzle. If muzzle exit occurs before this wave reaches the base of the projectile, the addition of more propellant to the system is superfluous. In fact, beyond a given travel, the projectile is no longer influenced by the conditions in the combustion chamber, i.e. pressure waves from the chamber cannot traverse the bore and overtake the projectile before it exits the muzzle. Therefore, any propellant burned after this critical projectile travel is reached, cannot contribute to an increase in muzzle velocity. This explains the flattening of the velocity vs. loading density curve for the RLPG. For the specific gun conditions used here, no increase in velocity is observed beyond a loading density of 1.05 g/cc.

It is important to note that, in the case of the RLPG, it is possible to obtain the desired propellant injection rate, and thus the gas generation rate required for constant pressure operation, purely by mechanical means. In fact, near-constant pressure operation has been demonstrated in experimental gun firings.[11]

Figure 9 shows loading density results for both a real (LGP 1845) and the hypothetical liquid (JA2) propellant. In the high loading density region, a 4% velocity difference is noted between the high energy JA2 and the moderate energy, lower flame temperature and low vulnerability LGP 1845. This implies that an increase in propellant energy may be desirable for anti-armor applications of the RLPG. However, such increases in propellant energy are usually accompanied by a degradation in vulnerability characteristics. To some extent the velocity difference can be compensated for by increasing the chamber volume, a degree of freedom not explored in this study.

Finally, we recognize that the intrinsic self-pumping aspect of the RLPG is achieved at the expense of a liquid propellant reservoir pressure higher than the peak chamber pressure. This consideration will increase the overall weight of an RLPG cannon. This increase may indeed be minimal in a system if total ammunition and gun weight are considered, due to the packing efficiency of LP.

IV. SUMMARY

Finally, Table 3 summarizes the best performance levels achieved for the different propulsion options. It appears that the current standard 120-mm round is quite well designed. Little margin for growth is possible by conventional means without changing some of the ground rules such as peak pressure and travel. Using unconventional propulsion techniques, muzzle velocity increases up to 25% over a well designed conventional round appear possible in principle. In practice, a 10 to 15% increase is likely to be the upper limit. It should be noted that the relative increases are by no means universal. They are very much system and ground rule dependent and must, therefore, be used in proper context.

TABLE 3. Best Performance of Each Propulsion Option

	STANDARD 120-mm				ENHANCED 120-mm			
Propulsion Option	CONV	CP	SPTC	RLPG	CONV	CP	SPTC	RLPG
Max. Muzzle Velocity (m/s)	1700.	1874.	2084.	1778.	1864.	2060.	2283.	1914
Loading Density (g/cc)	0.80	1.30	1.20	1.05	1.00	1.30	1.30	1.05
% Increase	base	10.2	22.6	~~0.5~~ 4.6	9.6	21.2	34.3	12.6

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